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Research Article

Hydrologic Variations and Stochastic Modeling of Runoff in Zoige Wetland in the Eastern Tibetan Plateau

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Hydrological time series data (1988–2008) of the Hei River, the main water source to Zoige wetland in the Eastern Tibetan Plateau, were investigated. Results showed that the runoff distribution of Hei River varies with the relative change in amplitude ($C_m = 15.9$) and the absolute change in amplitude ($\Delta Q = 37.1\ \mathrm{m^3/s}$) during the year. There was a significant decreasing trend since 1988 with annual runoff of 20.0 $\mathrm{m^3/s}$ (1988–1994), 19.0 $\mathrm{m^3/s}$ (1995–2000), and 15.2 $\mathrm{m^3/s}$ (2001–2008). There were double peaks in runoff during the water year: the highest peak in the period of 1988–2000 occurred in July while in the period of 2001–2008 it occurred in October. Shifting peak flow means less water quantity in wetland during growing season. Nearest neighbor bootstrapping regressive method was used to predict daily runoff of the Hei River. Model results show that it was fitted with 94.23% of R^2 for daily time series, which can provide a basis for the development and utilization of regional water resources.

1. Introduction

The Zoige wetland contains the largest high altitude wetland ecosystem in the world, which is over 5,000 $\mathrm{km^2}$ and ~3500 m above sea level [1]. The Zoige wetland ecosystem provides at least 30% of the water flowing into the upper reaches of the Yellow River (e.g., [2, 3]). However, the area of the wetland has been recently lost by desertification which is increasing at a rate of more than 10% per year [4–6]. The recent degradation of Zoige Peatland was often attributed to both the ditching drainage and climate change [3]. With the global warming becoming stronger, it will therefore become increasingly necessary to understand hydrologic processes to prevent further degradation (e.g., [7, 8]).

Hydrologic processes such as hydroperiod, flow duration and variability, and flood recession significantly impact the dynamics of wetland ecosystems [9, 10]. Times series approach to model hydrologic process and dynamics in river and stream has been well documented (e.g., [11–14]), since Thomas and Fiering [15] and Yevjevich [16] revealed that the hydrological phenomenon shows objective dependency on time domain and was described by the Markov model. Shinohara et al. [17] used a stochastic approach to explore the impact of climate change on runoff from a midlatitude mountainous catchment in central Japan. Verma et al. [13] explore the seasonal changes of soil moisture influenced by daily rainfall in New South Wales Australia using a stochastic model.

More recently, a couple of studies with stochastic model approaches have been published such as spatial and temporal distribution stochastic model in Raoli River basin in Sanjiang Plain and the hydrologic trend stochastic model in Wuyuer River in Zhalong wetland, Northeast China [18]. However, the stochastic models with hydrological time series used in alpine region are probably different from low elevation areas. So it is necessary to develop a stochastic model for runoff prediction in Zoige wetland in the Eastern Tibetan Plateau.

The objective of this study is to explore the Hei River runoff variations annually, monthly, and daily for a long term (1988–2008) and to understand hydrologic process during the wet and dry seasons and how the changes impact ecosystem of Zoige wetland in the Eastern Tibetan Plateau with climate

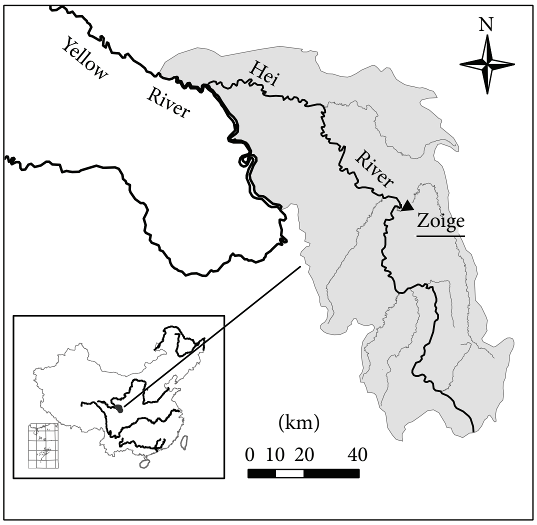

Figure 1: Location of the study area.

changes. Nearest neighbor bootstrapping regressive method was used to model the variations of daily runoff in order to provide a basis for the development and utilization of regional water resources.

2. Data and Methods

2.1. Data. Hei River is located in the Eastern Tibetan Plateau where wetlands are distributed widely. As the largest river in Zoige wetland, Hei River is the major tributary of the upstream of the Yellow River (Figure 1) and it flows from the south to the north and turns to the northwest at Zoige county town and flows finally to the Yellow River [19]. The length of the Hei River is 455.9 km, with an average gradient of 0.2% and the drainage area of 7608 km^2 [20]. There are many small lakes, which mostly are small swamps and oxbow lakes in the watershed.

We collected daily runoff, temperature, and precipitation during 1988 to 2008 at the Zoige hydrologic station in the Hei River middle reaches. The moving average method, Mann-Kendall testing method [21], and self-correlation diagram were used to analyze the trend and the dependency of the annual runoff, and homogeneous degree and variation and self-correlation diagram were used to analyze the distribution of the monthly runoff.

2.2. Nearest Neighbor Bootstrapping Regressive Model. Nearest neighbor bootstrapping regressive model (NNBR) is data driven and nonparametric, with potential priority, and needs no assumption in the form of dependence and probability distribution, as well as no estimate of many parameters [22–24].

Generally, there exists correlation between hydrology phenomena along timescale. Thus, to an extent, X_t depends on the historical daily runoff $Q_{t-1}, Q_{t-2}, \ldots, Q_{t-P}$. Given $D_t = (Q_{t-1}, Q_{t-2}, \ldots, Q_{t-P})$, it is named as eigenvector of the daily runoff series. Then, $X_t = (Q_t, Q_{t+1}, \ldots, Q_{t+m-1})$ $(t = P+1, P+2, \ldots, n-m+1)$ can be defined as the succeeding value of D_t.

Among D_t $(t = P+1, P+2, \ldots, n)$ which are constituted by $\{Q_t\}_n$, there must be some nearest neighbor eigenvectors to current eigenvector D_i. Suppose the number of nearest neighbor eigenvectors is K, and it is represented by $D_{1(i)}, D_{2(i)}, \ldots, D_{K(i)}$. $X_{1(i)}, X_{2(i)}, \ldots, X_{K(i)}$ must be the succeeding values of each corresponding eigenvector. The nearest neighbor is judged by the difference between D_i and D_t, which is defined as

$$r_{t(i)} = \left(\sum_{j=1}^{P} \left(d_{ij} - d_{tj} \right)^2 \right)^{1/2}, \tag{1}$$

where $r_{t(i)}$ represents the difference between D_i and D_t, d_{ij} and d_{tj} are number j variable of D_i and D_t, respectively, and P is the dimension of eigenvector. Then, $r_{j(i)}$ $(j = 1, 2, \ldots, K)$ is denoted by the difference between $D_{j(i)}$ and D_i, and it should be mentioned that $r_{1(i)} < r_{2(i)} < \cdots < r_{K(i)}$ (the number j is ordered according to the value of $r_{j(i)}$). The less $r_{j(i)}$ is, the nearer D_i and $D_{j(i)}$ will be, and X_i is more similar to $X_{j(i)}$. Let $G_{j(i)}$ be the nearest neighbor bootstrapping weight of $X_{j(i)}$, which shows similarity between X_i and $X_{j(i)}$. Obviously, $G_{j(i)}$ is related to $r_{j(i)}$.

As discussed above, the relative value of number i variable of number j nearest neighbor succeeding vector $X_{j(i)}$ is known. The succeeding vector X_i can be obtained through multiplying predicted daily runoff $G_{j(i)}$. Thus, the ultimate formula of NNBR model can be given as

$$X_i = \sum_{j=1}^{K} G_{j(i)} X_{j(i)}. \tag{2}$$

NNBR model is confirmed when the number of nearest neighbor K, the dimension of eigenvector P, and the nearest neighbor bootstrapping weight $G_{j(i)}$ are estimated.

Generally, $K = \operatorname{int} \sqrt{n-P}$ is given. If $P \geq 2$, the dimension of eigenvector P can be estimated by runoff autocorrelation graph or partial-correlation graph.

There are a number of methods to estimate bootstrapping weight $G_{j(i)}$. When estimating, first of all, its restraint condition must be satisfied, and then bootstrapping weight $G_{j(i)}$ should be related to $r_{j(i)}$, and the bootstrapping weight function should equal one (3). As the number j is ordered according to the value of $r_{j(i)}$, in this paper, the following formula is adopted:

$$\sum_{j=1}^{K} G_{j(i)} = 1, \tag{3}$$

$$G_{j(i)} = \frac{(1/j)}{\sum_{L=1}^{K} 1/L} \quad (j = 1, 2, \ldots, K). \tag{4}$$

When K is confirmed, we can only calculate $G_{j(i)}$ once.

We used the following qualification rate (QR) and coefficient of determination R^2 to estimate model fits for the calibration and validation. In this study, if the prediction of

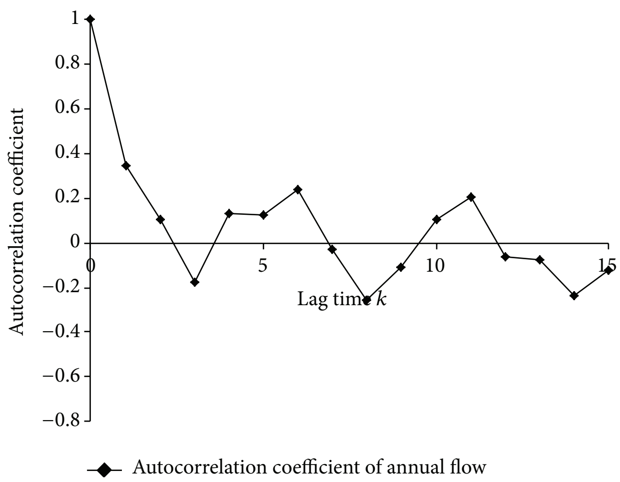

FIGURE 2: Autocorrelation coefficient and lag time of the annual runoff.

relative error was less than 20%, thus the model was assumed to be qualified:

$$\mathrm{QR} = \frac{n}{m} \times 100\%, \quad (5)$$

where n is the number of qualified predictions and m represents the totality.

3. Results and Discussions

According to the runoff observation data from 1988 to 2008 (except 1998) at Zoige hydrologic station, the average annual runoff is $20.40 \pm 1.70\,\mathrm{m^3/s}$, the average annual runoff depth is 161.0 ± 13.37 mm, and the average annual discharge is $(6.44 \pm 0.53) \times 10^8\,\mathrm{m^3}$, respectively.

The degree of dispersion of annual runoff time series is too large with the variation coefficient $C_v = 0.37$ and skewness coefficient $C_s = 0.2$. It is because Hei River belongs to the river with the rain-snow and ice fusion. Discharge of runoff depends largely on the precipitation variation and snowmelt [25]. However, because average annual runoff of the area itself is small, interannual variation of runoff is relatively small, which led to weak dependence of the annual runoff series (Figure 2).

During the period of 1988~2008, the largest annual flow occurred in 1999 (up to $32.6\,\mathrm{m^3/s}$), while the lowest annual runoff occurred in 2002, only $8.3\,\mathrm{m^3/s}$, respectively. Hei River runoff decreasing trend is remarkable since 1988 (Table 1 and Figure 3). The higher temperature and less precipitation led to the decreasing trend of runoff (Figures 4 and 5). From 1988 to 1999 is the abundant water period; from 2000 to date is the drier period. According to the observation data, the average annual flow from 1988 to 1994 is $27.0 \pm 0.75\,\mathrm{m^3/s}$ and the average annual flow has decreased to $19.0 \pm 1.24\,\mathrm{m^3/s}$ during 1995~2000 and $15.2 \pm 0.74\,\mathrm{m^3/s}$ during 2001~2008, respectively (Figure 3). The trend of decreased annual runoff impacted ecosystems of Zoige wetland and partly contributed to wetland degradation with habitats loss.

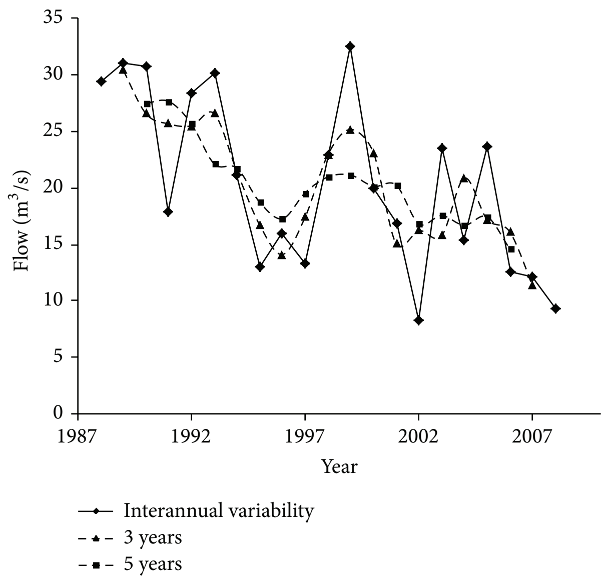

FIGURE 3: Trend of the variation of annual runoff.

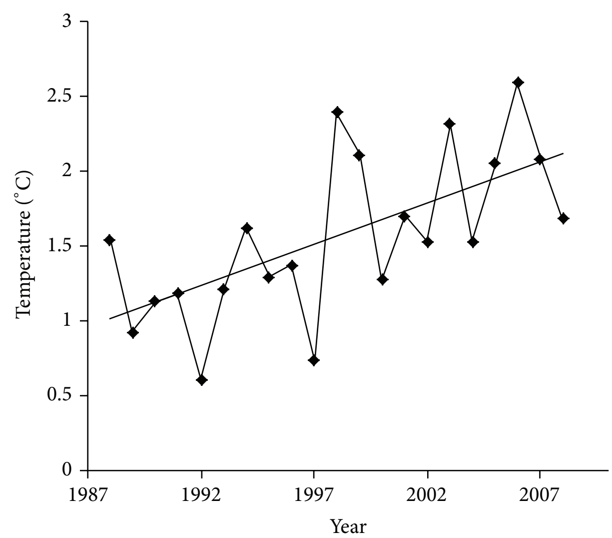

FIGURE 4: Trend of the variation of annual temperature.

TABLE 1: Tendency of the runoff series of years by Mann-Kendall statistical test.

Test statistic U	Significance α	Critical value $U_{\alpha/2}$	Judge result	Tendency
−2.92	0.05	1.96	$\lvert U\rvert > U_{\alpha/2}$	Significant decrease

The results of this study are consistent with previous findings of degradation of the wetland (−13.08% for swamp, −6.31% for river, and −20.24% for lake) from 1987 to 2004 that associated significantly with changes in hydrological processes [3]. Due to decreasing annual runoff, it resulted in the fact that overflow of water could not reach adjacent wetlands and led to wetland function loss [3].

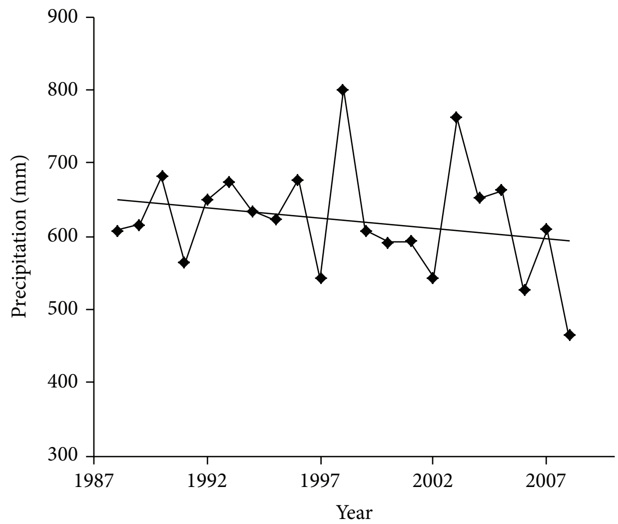

Figure 5: Trend of the variation of annual precipitation.

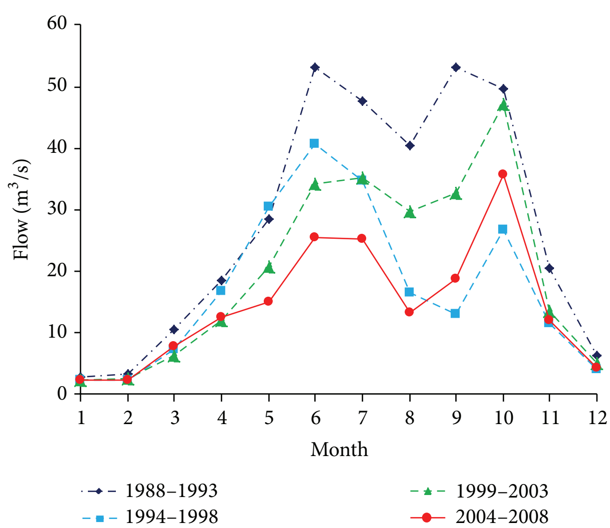

Figure 6: Monthly runoff distribution during 1988 to 2008 with a 4-year increment.

The monthly runoff distribution during the year is uneven (Figure 6), and the relative change amplitude C_m is 15.9 and absolute change amplitude is 37.1 ± 4.04 m^3/s. Peak runoff mainly concentrated in the months 5–10. This river is supplied at the same time by two ways: precipitation and snow and ice ablation. In winter, the runoff is very small because the low temperature makes the surface frozen. With the spring coming, it becomes swarm, but the temperature is still very low, and the wetland is covered by ice and snow, while in summer when the temperature is higher, peak flow occurred by precipitation, snowmelt, and the runoff of the river in summer. Pulsing flooding water during growing season made high net primary production from wetland plant communities [10, 26].

Dry season (December to February) contributes only 4.4% of discharges for all the year, while wet season (May to October) contributes 82.8% of discharges for all the year, respectively. The nonflood season (November to next April) contributes 17.2% of discharge for all the year (Figures 5 and 6). It may be because the precipitation's rapid decrease after July leads to the runoff's decrease, and the air temperature is still higher; it has led higher evaporation in August and September and lower in October. The highest peak in the period of 1988–1994 and 1995–2000 occurred in July while in the period of 2001–2008 the highest peak occurred in October (Figure 6). Shifting peak flow means less water quantity in wetland during growing season, which significantly impacts plant communities and also biogeochemical process [27]. The restoration approach used in Zoige wetland resulted in one peat-mining site being filled with water and aquatic vegetation with increased water levels up to 26–50 cm higher than previously recorded in canals and shallow water canal, respectively. Pioneering vegetation including *Eleocharis* Horsetail (*Equisetum, Eleocharis*) and Halerpestes (*Halerpestes tricuspis*) colonized in the restored sites [3]. The similar hydrologic function study was presented from peat wetlands in Canada where the impact of a change in hydrological function from transmitting to contributing on aquatic chemistry may depend on the residence time of water in the wetland. Shifting peak flow also contributed a short residence time in the wetland to not fully develop characteristic chemical traits of wetland ground water [28]. In general, natural- and human-induced factors may produce gradual and instantaneous trends and shifts (jumps) in hydroclimatic series. For example, the historical shifts in snowmelts suggested that an increase in global and regional temperature affected the discharge from a midlatitude mountain area of central Japan by using a simplified hydrological model and associated stochastic treatments [17, 29]. The occurrence of trends and shifts in hydrologic time series and the ensuing effects on water resources, the environment, and society still are concerned (e.g., [17]).

Table 2: Daily runoff prediction for 2008 of Hei River using NNBR model.

NNBR model	Mean of relative error (%)	QR (%)	R^2
	5.61	97.50	0.98

Through primary selection of the model parameters, trial and error, it determines that $P = 2$, nearest neighbor number $K = 33$. Then daily runoff of 1988~2007 is used to constitute the feature vector D_t, which is used to predict daily runoff of the year 2008. The QR is 97.50% and the R^2 is 0.98 (Table 2 and Figure 7) in validation phase owing to NNBR model's superiority.

Because NNBR model is data driven and nonparametric, it avoids the uncertainty of parameter and the problem of model choice which is different from other models based on the traditional prediction patterns of "assume-calibration-validation." So it was widely used to predict the hydrological series, such as the annual runoff of the Yangtze River in the upper reaches [30]. However, NNBR, the same as other models, would make no sense when the future motion trail of the series is out of the law obtained by its historical data.

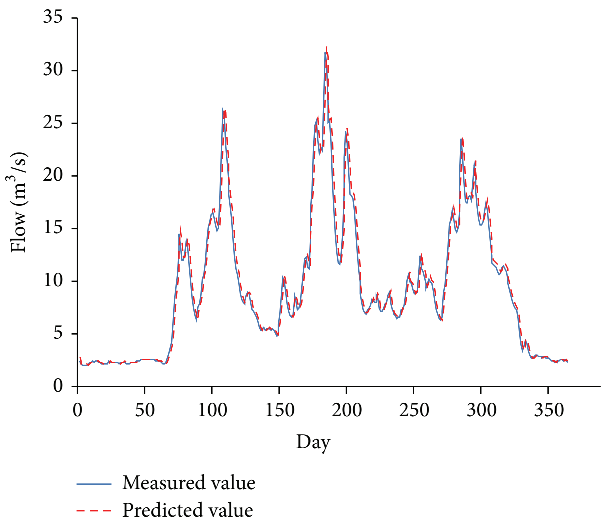

FIGURE 7: Daily runoff prediction for 2008 of Hei River using NNBR mode.

4. Conclusions

The annual runoff of Hei River decreased from 27.0 m^3/s (1988~1994) to 15.2 m^3/s (2001~2008). The monthly runoff distribution during the year is uneven, and the relative change amplitude C_m is 15.9; absolute change amplitude is 37.1 m^3/s. The maximum value of runoff appeared in July in 1988 to 2000 and shifted to October after 2000, which may be because of the precipitation's rapid decrease after July leading to the runoff's decrease, and the temperature is still high; evaporation force is strong in August and September while October evaporation is reduced, so the maximum appears.

A stochastic model and modeling schemes were developed for simulation of hydrologic processes of Hei River. Daily runoff modeling with NNBR model during 2008 has good fits with 97.5% which is probably more suitable than liner regressive model especially when the time series has no obviously short-dependency.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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